OPTICAL SATELLITE COMMUNICATIONS

GUEST LECTURE – COMMUNICATION THEORY

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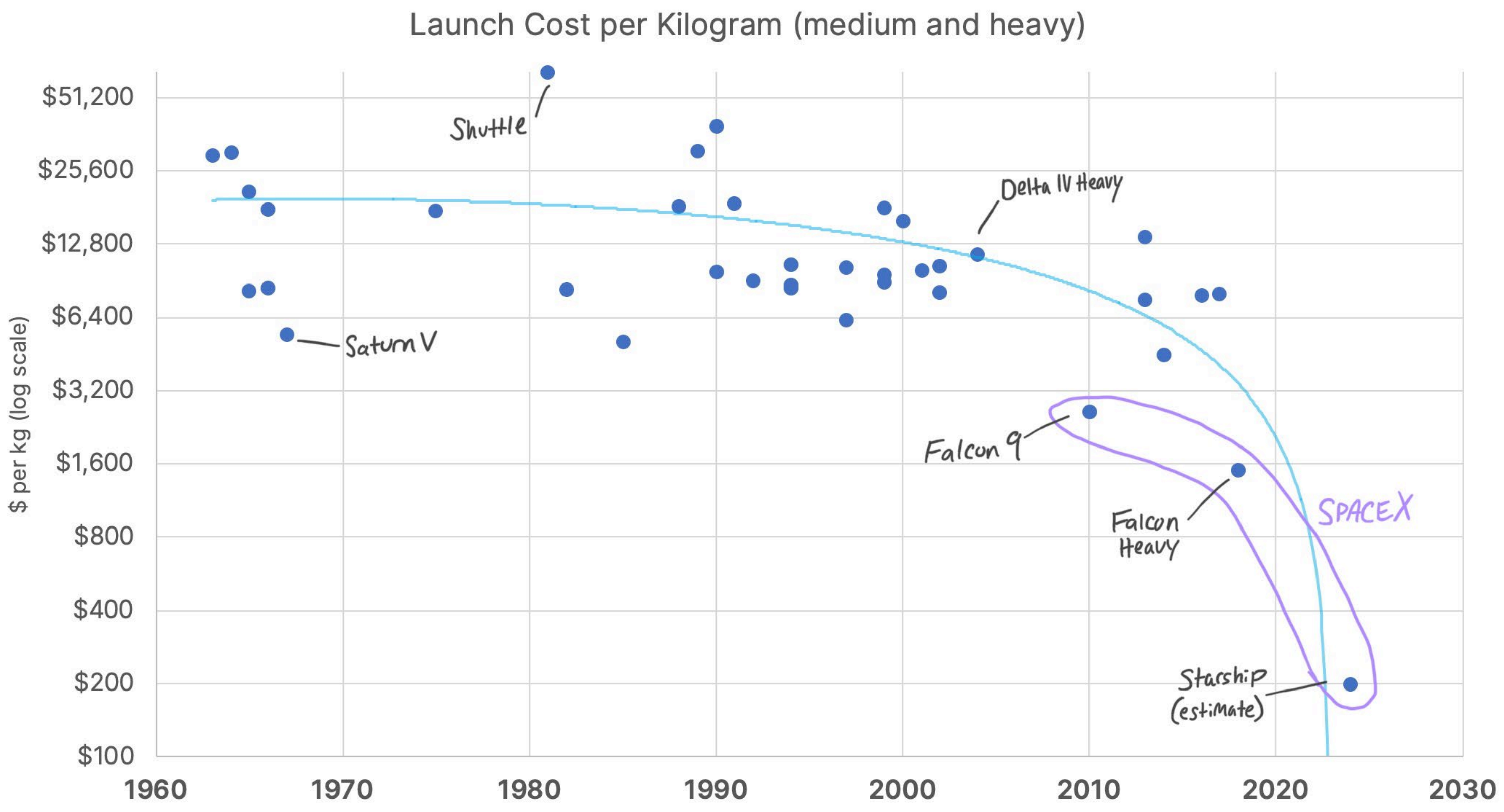
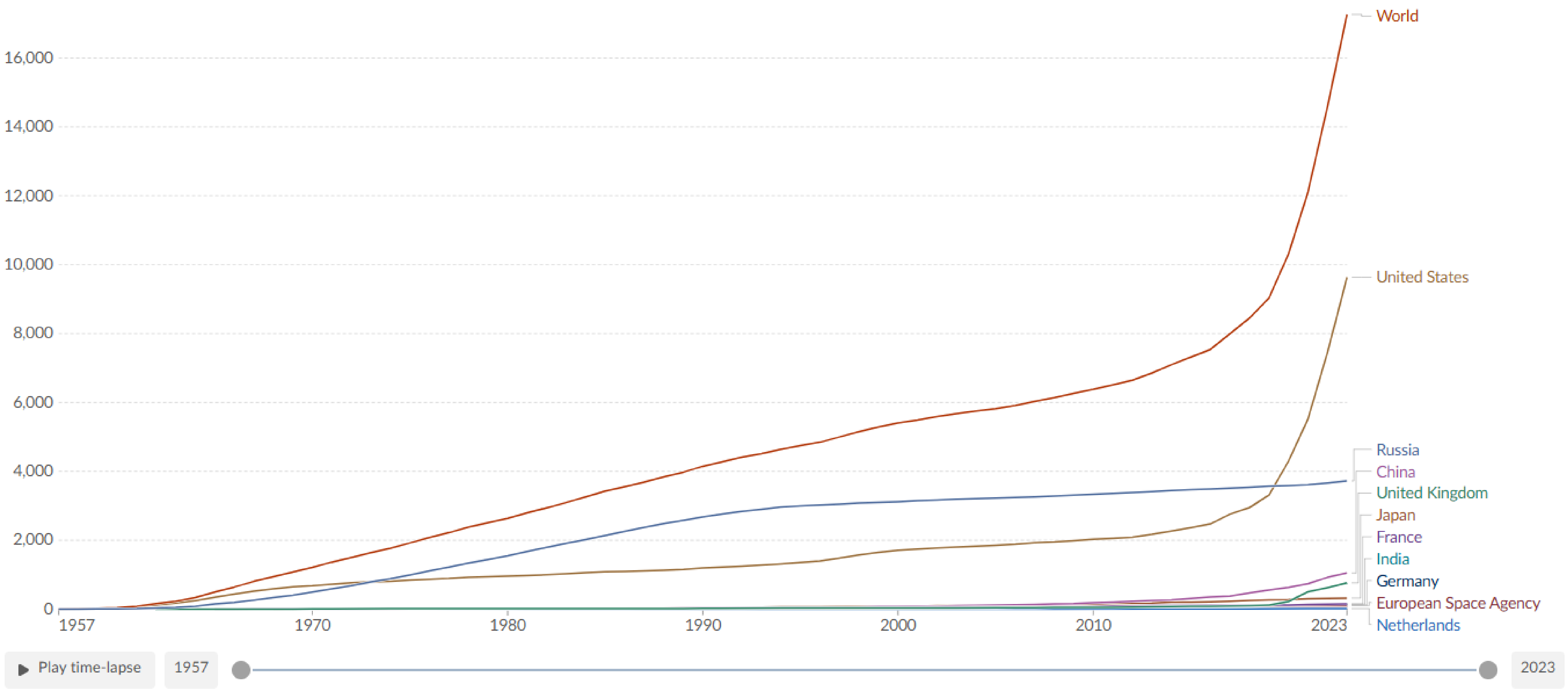
20th of January, 2025 - c.w.korevaar@tue.nl

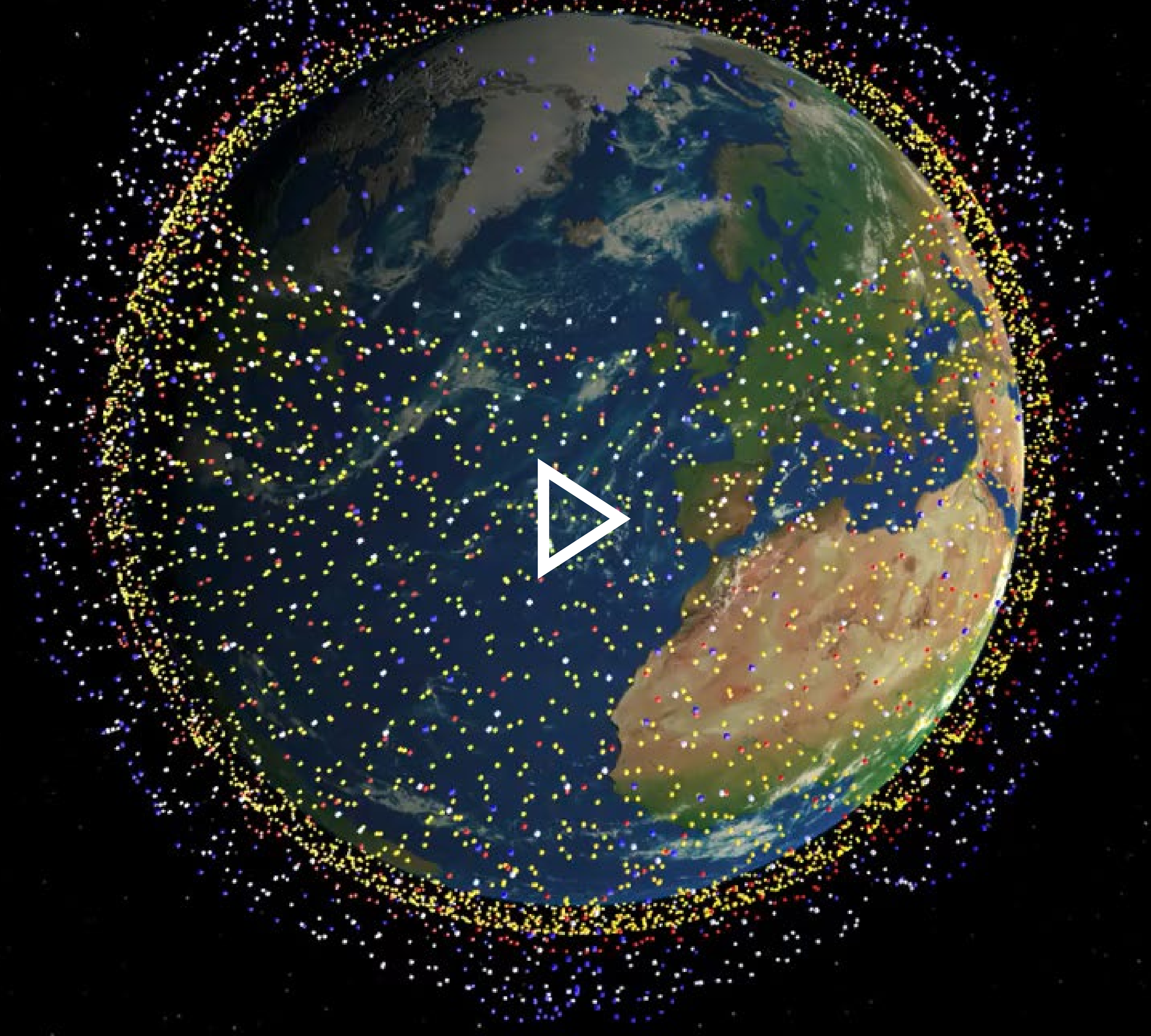
Courtesy KPN



Data from https://aerospace.csis.org/data/space-launch-to-low-earth-orbit-how-much-does-it-cost/

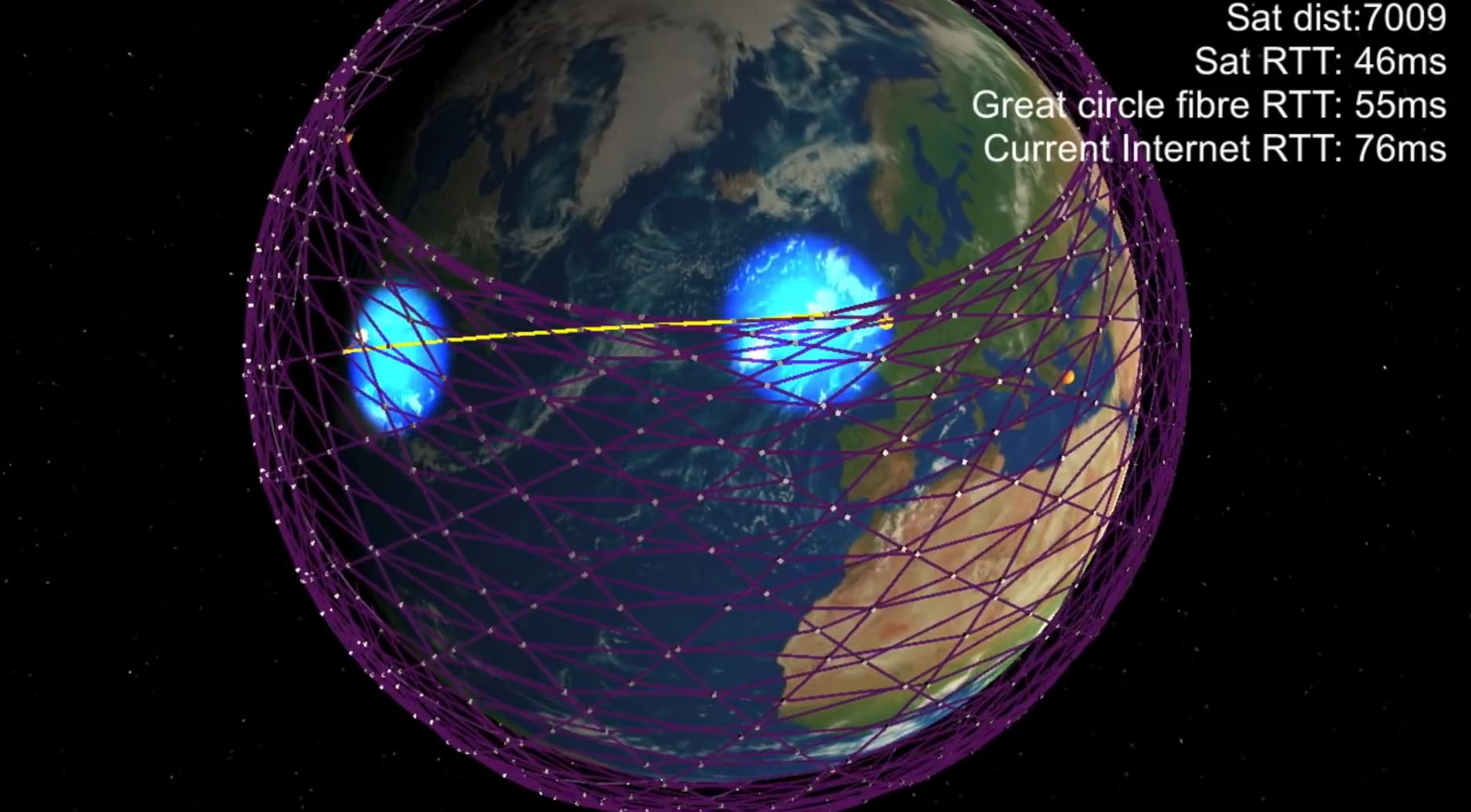


Data source: United Nations Office for Outer Space Affairs (2024) – Learn more about this data



Courtesy Mark Handley

SPECTRUM



Courtesy Mark Handley

FSO VERSUS RF – LINK BUDGET

- Receive power:

$$P_R = \eta P_T \cdot \left(\frac{\pi D_T}{\lambda}\right)^2 \left(\frac{\pi D_R}{\lambda}\right)^2 \left(\frac{\lambda}{4\pi R}\right)^2$$

- which is proportional to $\frac{1}{\lambda^2}$ and f^2.

- Example: **Ka-band versus FSO**
- with RF Ka-band (30 GHz) versus FSO C-band (193 THz)
- this gives about 75 dB gain in receive power for FSO over RF
- assuming antenna sizes D_T and D_R, transmit power P_T, distance R all the same.

Example #3: **100 Mbps link from Mars to Earth**

Parameter	RF Ka-band	FSO C-band	units
Wavelength λ	10^7	1550	nm
Frequency c/λ	30	193 550	GHz
Transmit power P_T	500	50	W
Transmitter diameter D_T	5.6	0.5	m
Receiver diameter D_R	4x 34	6x 2.5	m

By NASA B. L. Edwards, D. Antsos, A. Biswas, and others, "An envisioned future for space optical communications," 2023 International Conference on Space Optical Systems and Applications (ICSOS), 2023.

FSO VERSUS RF - RISK OF DETECTION & INTERCEPTION

Thanks to the high transmitter gains and high directivity

the FSO beams have a low probability of detection (LPD) and interception (LPI)

Diffraction-limited spot size (in far field, assuming perfect optics and antennas):

$$w(R) = w_0\sqrt{1+\left(\frac{\lambda R}{\pi w_0^2}\right)^2} \approx \frac{\lambda R}{\pi w_0}$$

Example: **Eavesdropping a LEO satellite on the ground**

with RF Ka-band (30 GHz) versus FSO C-band (193 THz), distance of 500 km

and a transmit beam waist radius w_0 of 10 cm gives +/- 15900 m for Ka-band versus 2.5 m for FSO link.

THE PROMISES OF FSO

- High-throughput
- High-security
- Low-interference
- Low energy-per-bit
- License-free

THE KEY CHALLENGES

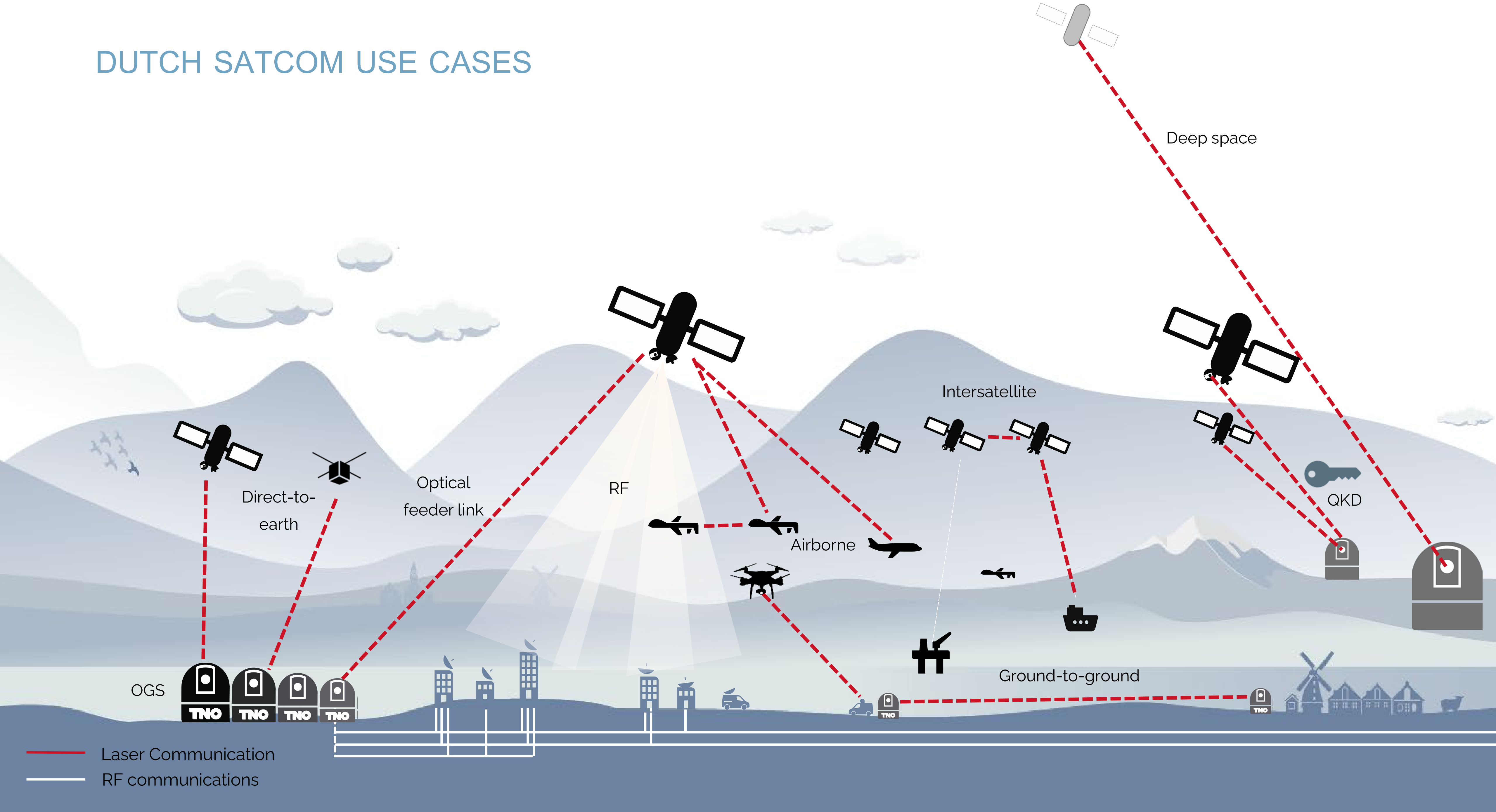
SOME KEY FACTORS

- **Availability** – limited by weather conditions
- **Locations** – direct line of sight
- **Eye safety** – limit on transmit power

TECHNOLOGICAL CHALLENGES

- Acquisition, tracking & pointing
- Atmospheric turbulence & robustness
- Modem & DSP design for Gbps/Tbps links

DUTCH SATCOM USE CASES



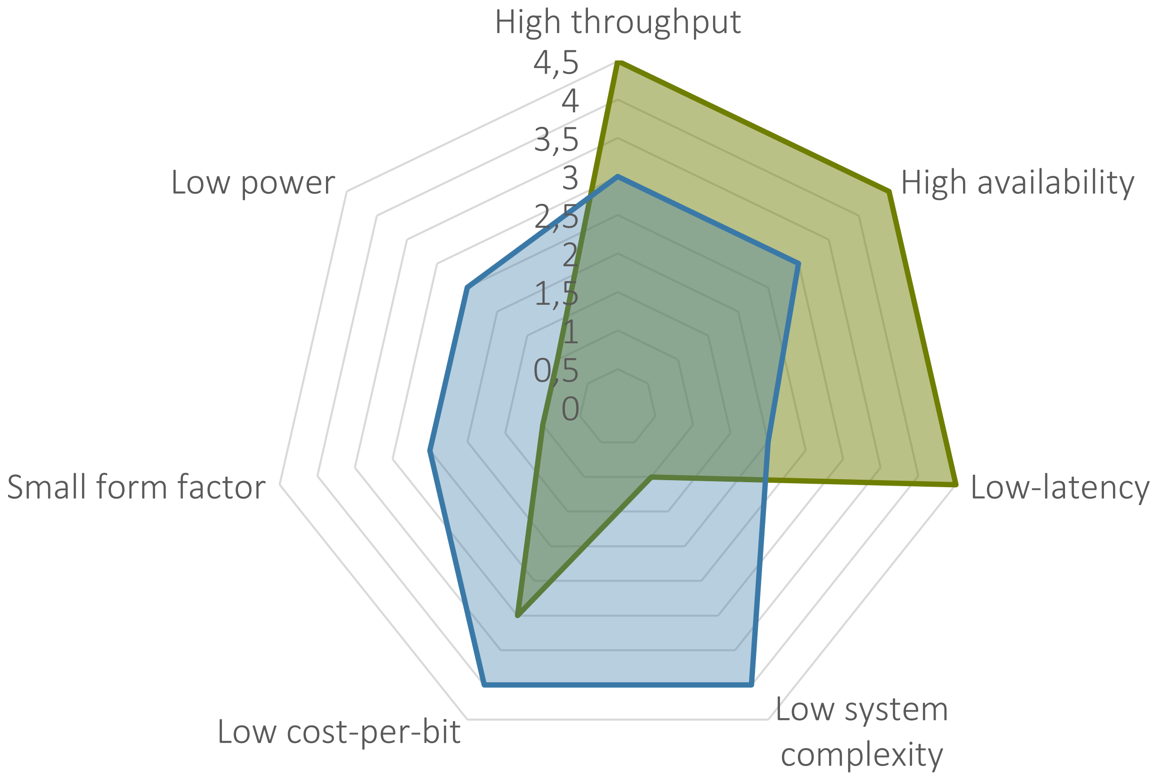
DEFINE KEY PERFORMANCE GOALS

TYPICAL OBJECTIVES:

- 1. THROUGHPUT
- 2. RELIABILITY
- 3. HIGH-AVAILABILITY
- 4. LOW-LATENCY

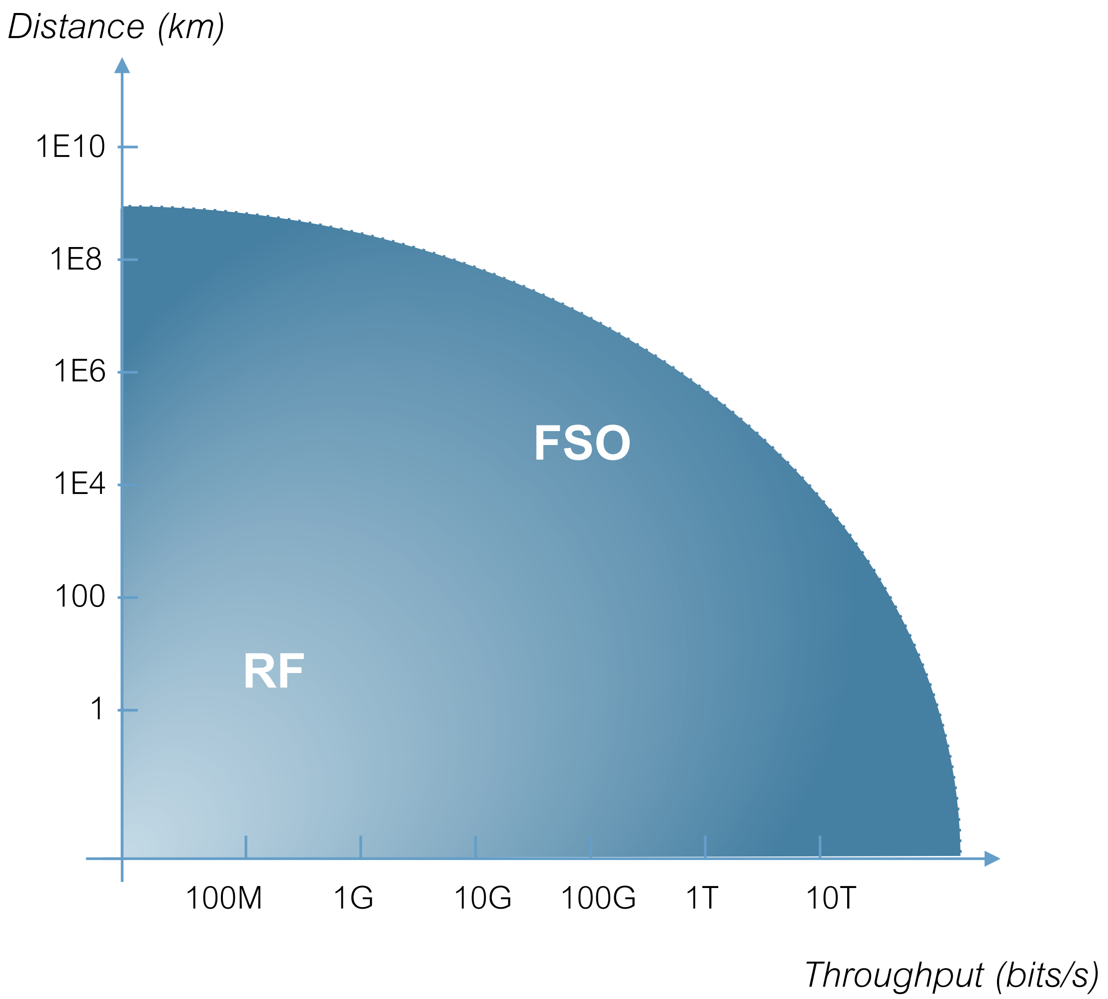
WHILE MEETING/MINIMIZING THE REQUIRED:

- COST-PER-BIT
- BANDWIDTH / WAVELENGTH
- POWER / EYE-SAFETY
- FORM FACTOR (SIZE & WEIGHT)
- SYSTEM COMPLEXITY
- ....

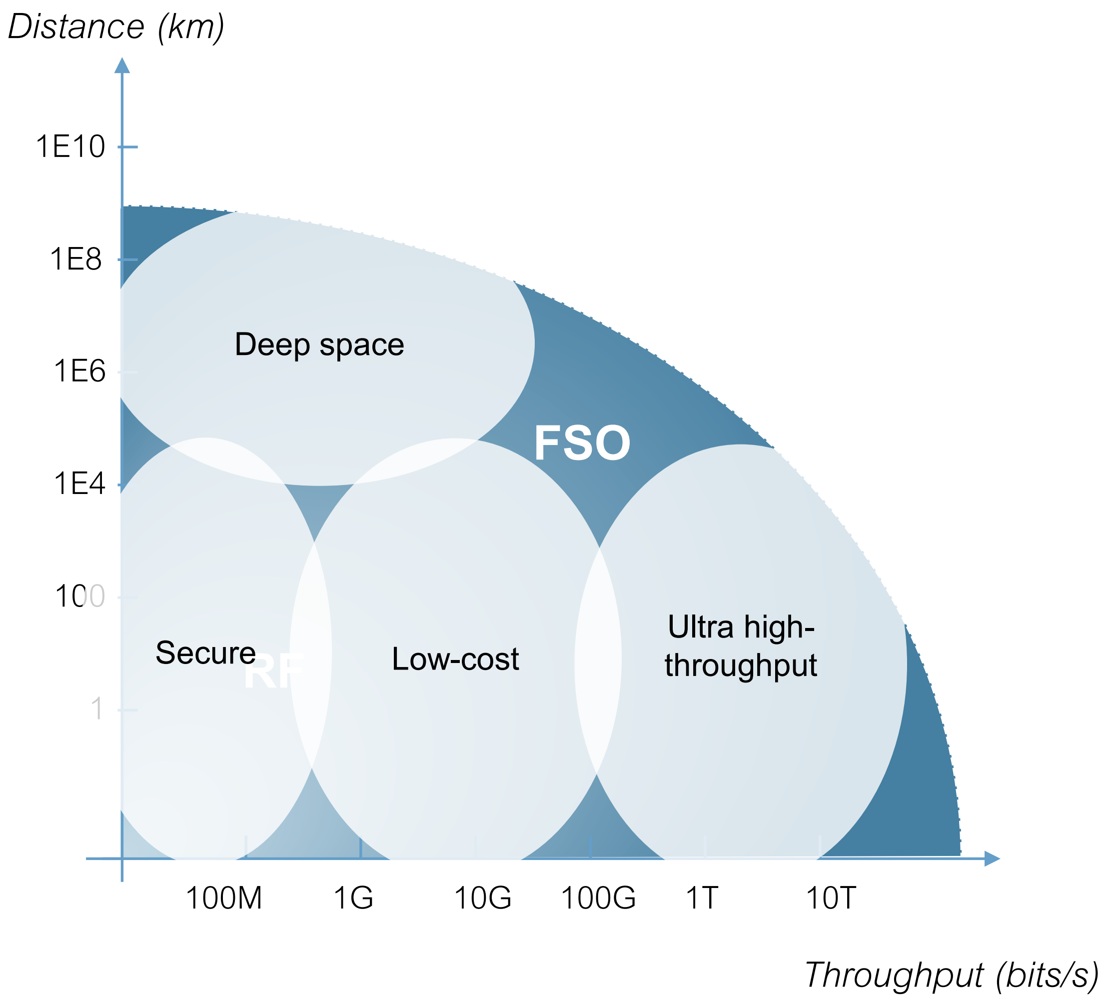


Example visualization of performance of two different designs

RF & FSO FIGURES OF MERIT



USE CASES FOR FSO



Use case & USP	Typical datarate	Modulation
1. Low-cost	Gbps class	OOK
2. High-throughput	Tbps class	WDM-QPSK
3. Deep space – Photon-efficient	Mbps - Gbps	PPM
4. Ultra-secure - QKD	bps - kbps	CV-DV QKD

ACHIEVABLE RATE – A MOONSHOT

Assume you want to set up an FSO laser link from the Moon to the Earth.

- You dimension your system such that 0.01 nW of average power is received.
- You may assume that we use single photon detectors, lossless receiver and no background noise.
- We use the NIR wavelength of 1550 nm.

Now the question, given 256-PPM, what is the achievable rate and photon efficiency?

<u>Example Moon link</u>:

The photon energy is $h \cdot f$, such that we have $P_{\text{TX}}/(h \cdot f)$ photons / second.

With M-PPM, you need M timeslots per symbol, to send $\log_2$ (M) bits per symbol.

If you only need one photon per symbol, and transmit $\log_2$ (M) bits per symbol, you'll need $1/\log_2(\text{M})$ photons-per-bit.

With P_{TX}=0.01 nW, we have 7.8E7 photons / second, with M=256, we get to 623 Mbps and get down to 0.125 ppb.

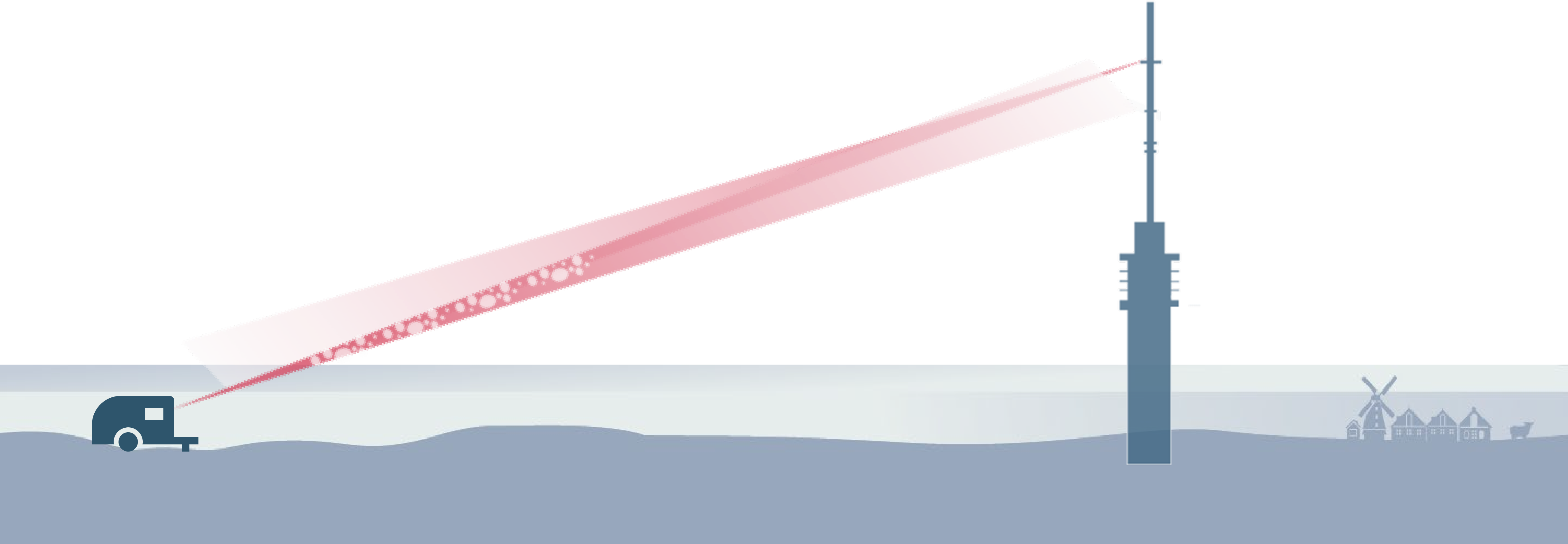
CALCULATE THROUGHPUT

- A. Number of optical channels, e.g. 96 x 50 GHz channels
- B. Baudrate per channel, e.g. 25 Gbaud per channel
- C. Modulation format, e.g., QPSK, 2 bits per symbol
- D. FEC & coding rate, e.g., coding rate of 0.9 means 90% is used for actual data
- E. Polarizations, e.g., 2 for dual-polarization doubles the throughput
- F. Transmission success factor, e.g., 0.99, on average 1% of retransmissions
- G. Overhead, headers & protocols, e.g., 0.9 to account for 10% overhead

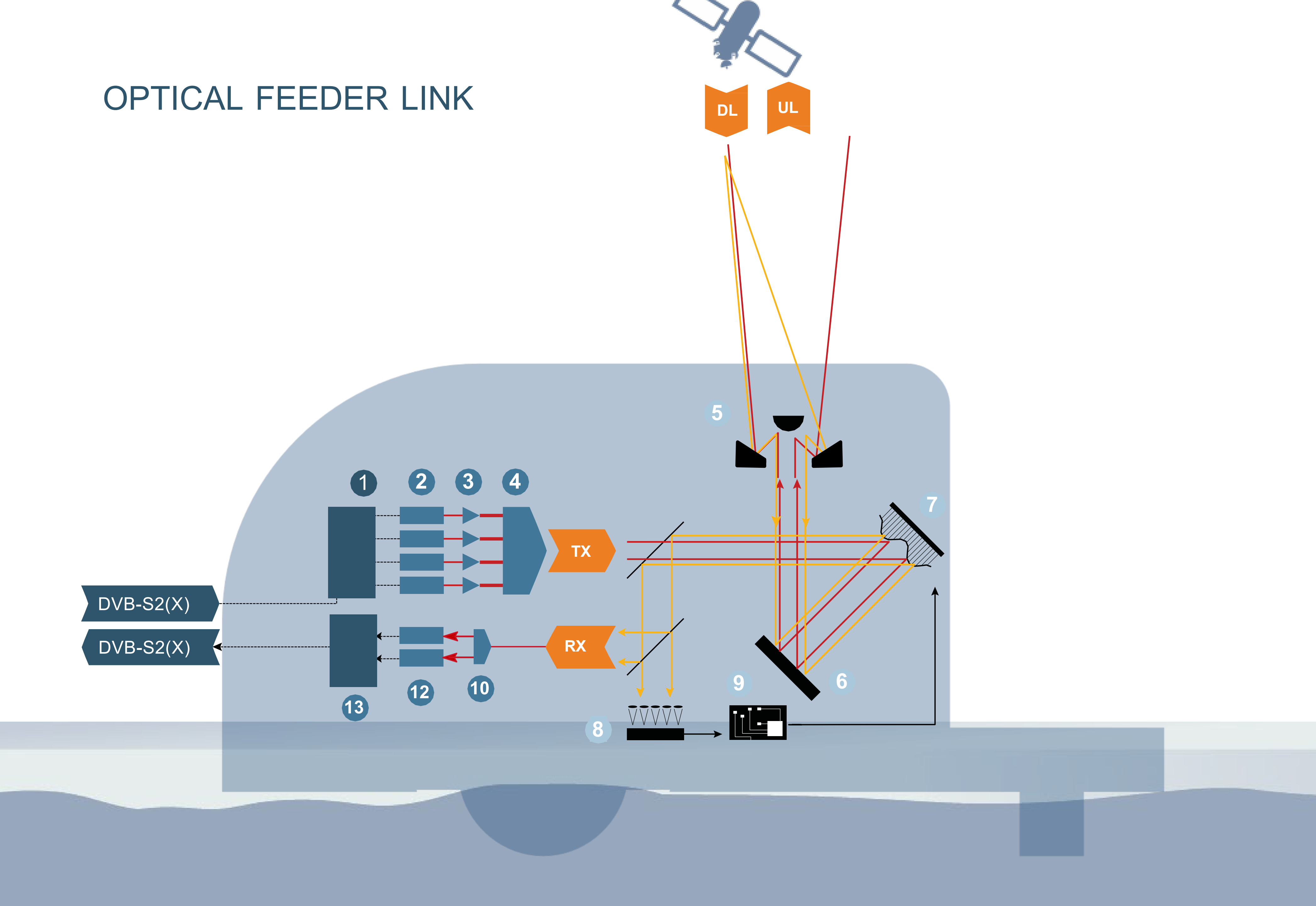
Estimated throughput is: A x B x C x D x E x F x G

(*for the example values you get:* 7.8 Tbps)

OPTICAL FEEDER LINK



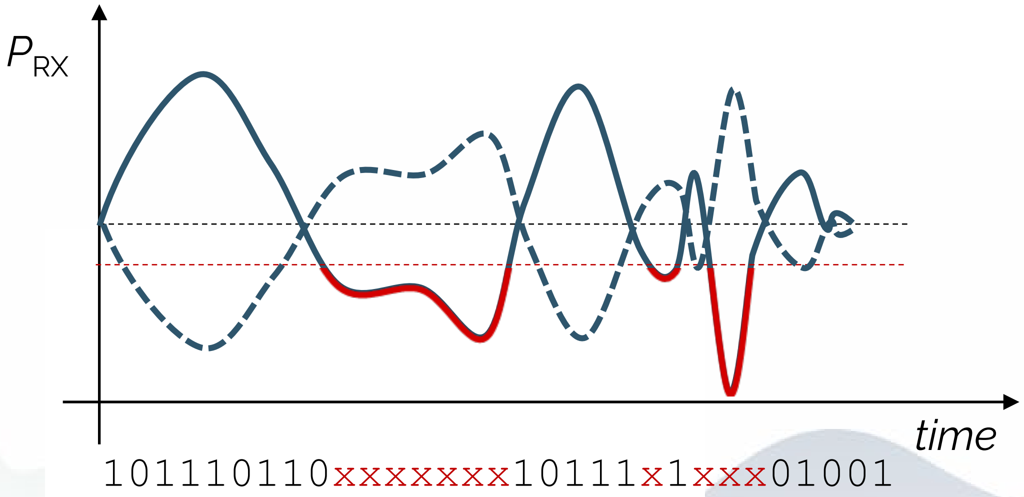
OPTICAL FEEDER LINK



1. Digital Processor
2. Optical modulators
3. Booster amplifier
4. High power multiplexer
5. Telescope
6. Tip/tilt corrector
7. Deformable mirror
8. Wavefront sensor
9. Control system
10 De-multiplexer
11 Preamplifier
12 Detectors, LIA, TIA & CDR
13 Digital processor

- Retransmissions
- Overdimensioning
- *Power precompensation* *
- *AO precompensation* *

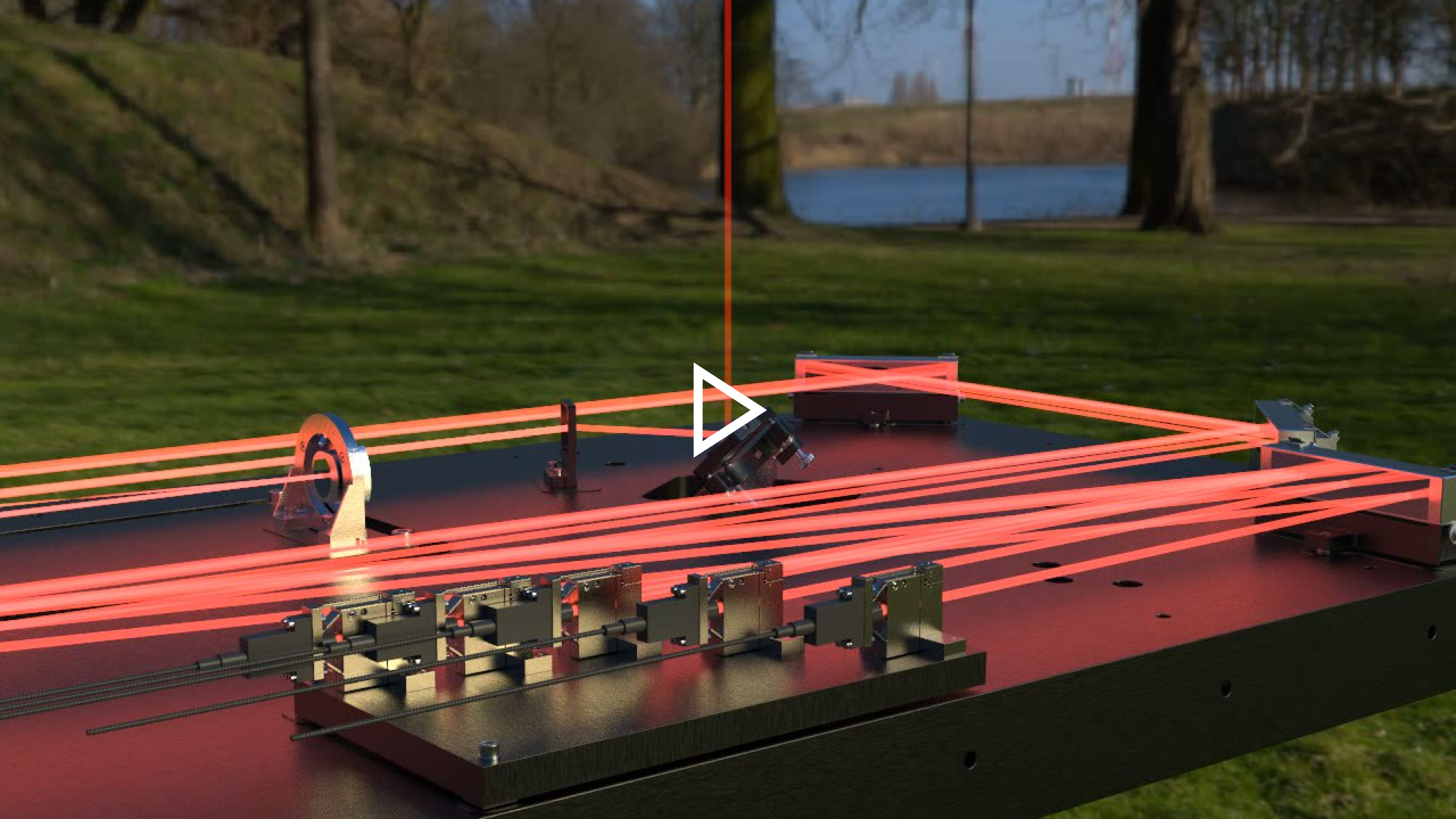
THE PROBLEM OF FADING & MITIGATION METHODS



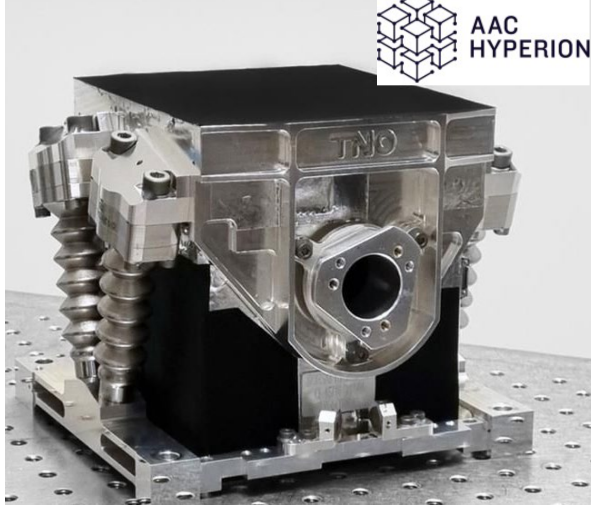
* *Assuming CSI @ TX*

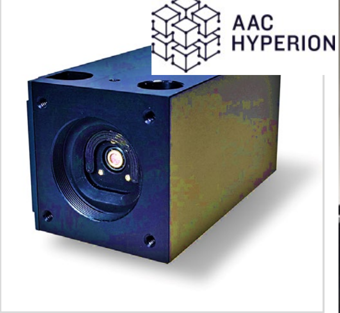
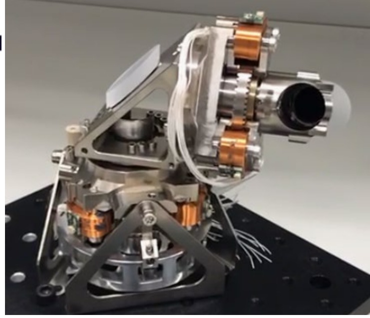
THE PROBLEM OF FADING & DIVERSITY METHODS

- Temporal diversity
- Spatial diversity
- Site diversity
- Frequency diversity

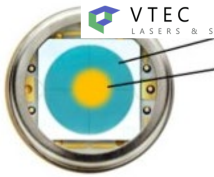


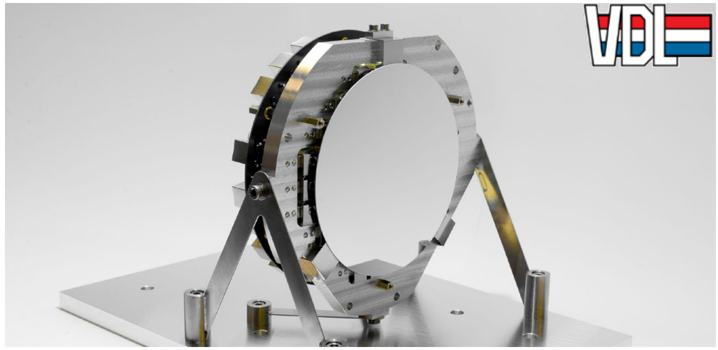
https://www.youtube.com/embed/UxPj_k1zAzM


AIRBUS
TNO innovation for life
AIRBUS

AAC HYPERION
TNO

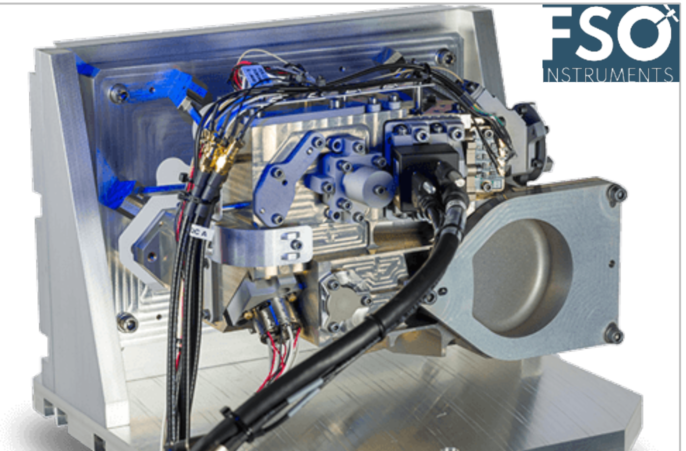
DEMCON
TNO

AAC HYPERION


EFFECT
PHOTONICS

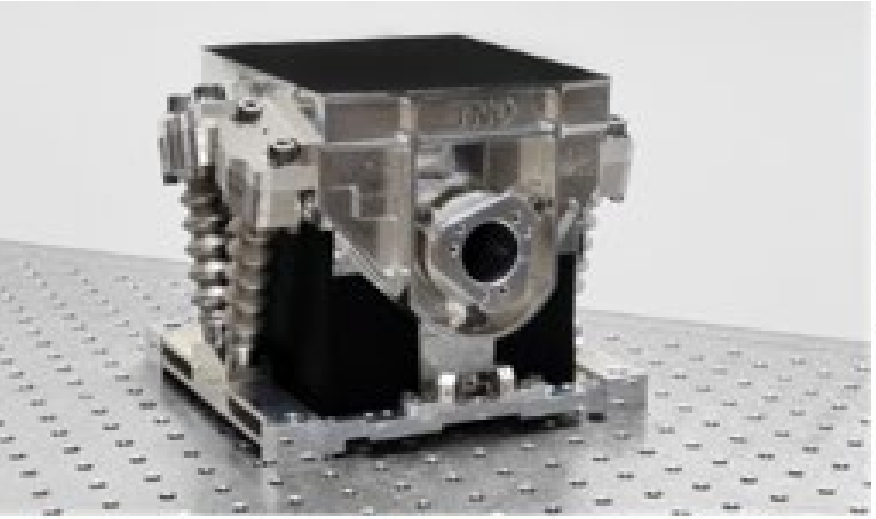
Optical Digital Converter
csts

VTEC

AIRBUS

VDL

AIRCISION

SINGLE QUANTUM

FSO
INSTRUMENTS

AIRBUS



Transporter-7 Mission - YouTube

https://www.youtube.com/embed/MEXXI0j4Bz8

THANK YOU | Q&A

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